

HIGH SPEED, PRECISION MOTION STRATEGIES  
FOR LIGHTWEIGHT STRUCTURES

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## SUMMARY

The work during the period covered by this report proceeded along the lines of the proposal, including work on three aspects of the high speed motion planning and control of flexible structures: fine motion control, gross motion planning and control, and automation using light weight arms. In addition, work on modeling of the large manipulator arm to be used in experiments and theory has lead to some contributions in that area. These aspects will be found somewhat distributed through the modules reported below.

Conference, workshop and journal submissions and presentations related directly to this support totaled seven, and are listed in the references. Copies of the written papers or abstracts are attached.

Four students are involved in this work. S. Cetinkunt will finish his Ph.D. degree in a matter of months. He is considering a University research and teaching career. D. Lee and J. Kwon are preparing their Ph.D. Thesis proposals, and J. Huggins is completing his Master's Thesis this Fall, and will be taking the Ph.D. Qualifying Exam. This grant has previously supported G. Hastings, who is now on the faculty at Clemson U. and continuing research in the same general areas.

## GROSS MOTION PLANNING AND CONTROL

Sabri Centinkunt

Research in this area seeks to develop advanced strategies for "high speed, high precision motion planning and control of lightweight manipulators" with the following properties:

1. Wide range of motion speeds should be possible within the prespecified precision.

2. Precision motion via a) Joint space tracking accuracy, b) Flexible vibration control,
3. Robustness with respect to a) payload variations, b) Sensor noises due to environment and hardware disturbances, c) system nonlinearities that will become dominant at high speed motions.

In searching for high performance motion planning and control strategies for lightweight arms, a logical first step is to look at the performance of rigid model based strategies and identify their shortcomings. The following well-known rigid model based control strategies are studied when applied to flexible arm models, with typical trajectory planning algorithms, i.e. trapezoidal profiles:

1. Computed Torque Method (CTM),
2. Decoupled Joint Controller, plus gravity compensation (DJC + g),
3. Independent Joint Controller, plus gravity compensation (IJC + g),
4. Adaptive Model Following Control

Notice that these control strategies do not consider the arm flexibilities, and yet they are applied to real systems which exhibit structural flexibilities. The results of our studies on the performance of these controllers are summarized below:

1. Maximum speed of motion, achievable by (CTM, DJC+g, and IJC+g), is limited by the arm flexibility to the 1/3 of lowest clamped-cantilever frequency of arm. AMFC can achieve speeds twice as high by adaptively compensating nonlinearities under parameter uncertainty.

## 2. Precision Performance:

a) Joint tracking performance is closely related to the speed of motion and arm flexibility. For slow motions (relative to arm flexibility) joint space tracking performance is very good. When high speed motion is attempted, this performance deteriorates.

b) Flexible vibration control performance of rigid model based controllers give surprising results. All of the controllers successfully damp out the high frequency vibrations. However, low frequency vibrations do persist and cause large deflections. At this point, it is clear that the major problem for more advanced control strategies is to control low frequency vibrations as oppose to high frequency vibrations.

3. Robustness of non-adaptive controllers depends on the ratio of the speed of motion and bandwidth of the closed loop system. Closed loop systems with high bandwidth can tolerate parameter uncertainty (payload variations). For high speed, high performance manipulation classical rigid body based control strategies are not appropriate and not robust. Rigid model based AMFC has better robustness properties. The robustness can be improved by considering the flexible body dynamics.

In summary, classical rigid model based non-adaptive control strategies are not suitable for high speed, high precision manipulation. By the basic design principles, speed is compromised for robustness and precision is lost by ignoring flexibility.

## COMBINED CONTROL AND PLANNING STRATEGY

Sabri Centinkunt

It is now clear that for high speed and precision manipulation, control and planning methods must account for the arm flexibilities.

A new combined control strategy is being studied. Any given desired motion is considered as consisting of two phases: 1. Gross motion phase, 2. Fine Motion phase. In Phase 1, arm moves from one position to another with high speed. At this phase speed is the essential issue. Towards the end of the

motion, Phase 2, arm will interact with objects and accuracy is of prime importance. Clearly, each phase of motion has different emphasis, "High Speed" is the main issue in Phase 1, whereas "precision" is in the main issue in phase 2. Approach and leads to a new combined control strategy.

In phase 1, arm is controlled by a AMFC, which is designed based on a reduced order model to provide high speeds and robustness. In phase 2, full state feedback control methods are employed for fast, accurate positioning and vibration control of the arm. At this phase arm static deflections are included in the position and vibration control.

Furthermore, in the past it was believed that the desired joint space trajectory effectively determined the flexible body response under any feedback control. Our analysis shows that the controller used in the realization of a desired trajectory has important influence on the flexible body dynamics. As a result, for lightweight arm, planning and control must be studied together, as opposed to the totally separate design stages of rigid manipulators.

The initial results have been very encouraging. The completion of this work is expected very shortly, and results will be presented in the appropriate forums.

#### MODELING OF CONSTRAINED FLEXIBLE DYNAMICS

J. Lee

Unlike a conventional serial manipulator, a parallel link driven manipulator has an advantages of a high structural rigidity without increasing weight and lower interaction between links. Research on a closed chain mechanism is rare because there has not been an efficient computational method. In recent years, a reduction method using singular value decomposition that

eliminates the constraint force explicitly from the equation of motion has been developed and applied to multibody rigid systems with constraints. This reduction method is being used to analyze the dynamics of a flexible manipulator with a closed kinematic chain. The mode shapes of a multilink manipulator are very difficult to find since exact boundary conditions depend on the configuration of the manipulator. The assumed mode shapes of each link were verified by comparing the analytical method, a finite element method and experiment.

In the coming months, after the dynamics of a flexible manipulator with a closed chain is established, a constrained motion such as contour surface following or material handling aided by an overhead crane will be analyzed using this method and compared with unconstrained motion. One of the many recent robot control algorithms will be chosen to explore the robots dynamic behavior. One purpose of this research is to check that the control scheme is also insensitive to an environmental change such as switching between free motion and constrained motion.

## SYMBOLIC MODELING OF SERIAL FLEXIBLE MANIPULATORS

Sabri Cetinkunt

The modeling needs for this project has lead to a new systematic algorithm to symbolically derive the full nonlinear dynamic equations of motion of multilink flexible manipulators. Lagrange's equations and the assumed mode method are the basis of the new algorithm and they are adapted in a way suitable for symbolic manipulation by digital computer. Implementation of the algorithm on a commercially available symbolic manipulation program has lead to the generation of the equations currently being used in the research on two link serial arms.

## EXPERIMENTAL VERIFICATION

J. Huggins

Experiments to determine the dynamics of the flexible arm about a single point (linearized, for small motions) have been performed and the results with two other analytical methods, a finite element method and the assumed modes method are compared. The next experiments that need to be performed are the ones that will analyze the motion of the flexible arm while undergoing large motions (non-linear motions). To do these experiments, the Microvax II will be used to control the motion of the robot arm and to acquire and analyze the data.

To accomplish these latter goals, the inverse kinematics of the flexible arm have been solved and a software program written to use the forward and inverse kinematics to perform straight line planning. The path planning incorporates polynomial smoothing to eliminate jerkiness of the motion implements the path desired. This software will be general in nature so that a user can quickly add various control strategies while using the same path planning methods. The software will also gather vibration data that can be analyzed both in the frequency domain and in the time domain.

## FINITE ELEMENT MODELING OF THE LARGE FLEXIBLE ARM

D. Kwon

In order to understand the results obtained through experiments and relate them to the assumed mode model, a reliable representation of linear flexible behavior was needed. A commercial finite element modeling package, SUPERTAB, was used for this purpose. By changing the finite element model to closely represent the detail of the experimental setup, or to represent the assumptions

of the simplified and linearized assumed mode model, the results of either could be closely approximated. This was an important step in verifying the operation of each, the assumptions, and understanding the limitations of the assumed mode model.

## ANALYSIS OF AUTOMATION USING UNCERTAINTY

D. Kwon

The flexibility observed in a light weight arm is one form of dynamic uncertainty which is present in automation in many forms. Friction, inaccurate construction and fixturing, sensor noise, and thermal expansion are additional forms. For any given task to be successfully completed, the uncertainty in the robot state must be reduced to an acceptable level, dependant on the tolerance of the task. Several means are employed to reduce uncertainty, including rigidity and precise construction, end point sensing and feedback, and fixturing of the work piece relative to the robot. Although these concepts have been implicit in robot system design for many years, little has been done to formalize the treatment of the concepts to make them useful for system conceptual or detail design. This is now being undertaken with the current research which will form the basis of a Ph.D. Thesis. The experimental prototype that will be used in exploring these concepts will be the light weight arm and, in particular, the bracing strategy for reducing uncertainty.

## REFERENCES

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